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TABLES OF THERMIONIC PROPERTIES OF THE ELEMENTS AND COMPOUNDS

by Kenneth Carr
Rose Polytechnic Institute
Terre Haute, Indiana

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D.C. • 1967

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FOREWORD

The following compilation of thermionic and (related) properties of elements and compounds has been compiled for the convenience of those working in the emission physics area. The values listed have been cursorily checked but should not be used as referenceable information without confirming the value in the original reference.

These tables were compiled by Dr. Kenneth Carr, Associate Professor of Mechanical Engineering, Rose Polytechnic Institute, during the 1966 Case-Lewis Summer Faculty Fellowship Program.

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TABLE I. - VAPOR PRESSURES AND ELECTRONIC PROPERTIES FOR SOLID AND LIQUID ELEMENTS

Symbol	Element	Reference	Work function φ, ev [1],[2],[6]	Ionization potential V_i, ev	Melting point, °K	Vapor pressure (Torr) at temperature (°K)[8]		Temperatures (°K) for vapor pressures (Torr) [8]				
						1000	2000	10^{-2}	10^{-1}	1	10	10^{2}
Ac	Actinium	3	2.7*	6.9	1320 ± 50	10^{-12}	3×10^{-2}	1905	2100	2350	2660	3030
Ag	Silver	3	4.3	7.574	1234	4×10^{-6}	50	1300	1435	1605	1815	2100
Al	Aluminum	2	4.08	5.984	932	6×10^{-6}	6	1490	1640	1830	2050	2370
Am	Americium		--	6.0	< 1103-1269	3×10^{-6}	9	1375	1540	1745	2020	2400
As_4	Arsenic	1	5.11	9.81	1090	--	--	550	590	645	712	795
At_2	Astatine		--	--	575	--	--	364	398	434	480	540
Au	Gold	1	4.58	9.22	1336	5×10^{-10}	6×10^{-1}	1670	1840	2040	2320	2680
B	Boron	1	4.5	8.296	2300 > 2420	--	1.6×10^{-4}	2300	2520	2780	3100	3500
Ba	Barium	3	2.49	5.210	983	1.3×10^{-1}	--	883	984	1125	1310	1570
Be	Beryllium	2	3.92	9.32	1556			1500	1650	1830	2080	2390
Bi	Bismuth	1	4.28	7.287	544.5	4×10^{-2}		945	1050	1170	1350	1570
C	Carbon		4.60	11.256	--	6×10^{-8}	--	2730	2930	3170	3450	3780
Ca	Calcium	1	2.76	6.111	1123	2.4×10^{-1}	--	870	962	1075	1250	1475
Cd	Cadmium	2	4.07	8.991	594	5×10^{2}	--	538	593	665	762	885
Ce	Cerium	1,3	2.7	6.91	1177	--	1.6×10^{-2}	1970	2180	2440	2780	3220
Co	Cobalt	2	4.40	7.86	1768	--	2.5×10^{-1}	1790	1960	2180	2440	2790
Cr	Chromium	3	4.58	6.764	2176	8×10^{-10}	1	1670	1825	2010	2240	2550
Cs	Cesium	2,3	1.81	3.893	301.8	--	--	428	482	553	643	775
Cu	Copper	1	4.47	7.724	1357	1.2×10^{-8}	3	1530	1690	1890	2140	2460
Dy	Dysprosium	3	3.09	(6.82)	1680 ± 5	5×10^{-7}	15	1390	1535	1710	1965	2300
Er	Erbium	3	3.12		1770 ± 15	2×10^{-7}	7	1450	1605	1800	2060	2420
Eu	Eurgsium	3	2.54	5.76	1099 ± 10	1.4×10^{-1}	--	884	981	1100	1260	1500
Fr	Francium	3	1.8*	--	300	--	--	410	462	528	620	760
Fe	Iron	1	4.36	7.87	1809	10^{-11}	3×10^{-1}	1750	1920	2130	2390	2740
Ga	Gallium	1	3.96	6.00	302.9	7×10^{-7}	13	1405	1555	1745	1980	2300
Gd	Gadolinium	3	3.07	6.16	1585 ± 15	3×10^{-9}	2	1600	1760	1955	2220	2580
Ge	Germanium	1	4.56	7.88	1210	3×10^{-10}	6×10^{-1}	1670	1830	2050	2320	2680
Hf	Hafnium	1,3	3.53	7.0	> 2400	--	2×10^{-6}	2670	2930	3240	3630	4130
Hg	Mercury	1,3	4.52	10.43	234.29	--	--	319	353	398	458	535
Ho	Holmium	3	3.09	--	1734 ± 5	2×10^{-7}	7	1450	1605	1800	2060	2410
In	Indium	3	3.8	5.785	429.3	9×10^{-4}	90	1220	1355	1520	1740	2030
Ir	Iridium	1	4.57	9.00	2727	--	5×10^{-8}	2770	3040	3360	3750	4250
K	Potassium	3	2.22	4.339	336.4	5.4×10^{2}	--	481	540	618	720	858
La	Lanthanium	1	3.3	5.61	1193	--	10^{-2}	2000	2200	2450	2760	3150

TABLE I. - VAPOR PRESSURES AND ELECTRONIC PROPERTIES FOR SOLID AND LIQUID ELEMENTS (Cont'd)

Symbol	Element	Reference	Work function φ, ev [1],[2],[6]	Ionization potential V_i, ev	Melting point, °K	Vapor pressure (Torr) at temperature (°K)[8]		Temperatures (°K) for vapor pressures (Torr) [8]				
						1000	2000	10^{-2}	10^{-1}	1	10	10^{2}
Li	Lithium	3	2.38	5.39	453.69	7×10^{-1}	--	810	900	1020	1170	1370
Lu	Lutetium	3	3.14		1925 ± 5	10^{-11}	7×10^{-2}	1845	2030	2270	2550	2910
Mg	Magnesium	3	3.64	7.644	923	10		712	782	878	1000	1170
Mn	Manganese	3	3.83	7.432	1517	5.3×10^{-5}	1.2×10^{2}	1210	1335	1490	1695	1970
Mo	Molybdenum	2	4.20	7.10	2890	--	2×10^{-7}	2800	3060	3390	3790	4300
Na	Sodium	1	2.27	5.138	370.98	1.3×10^{2}	--	562	630	714	825	978
Nb	Niobium	1	3.99	6.88	2770	--	5×10^{-9}	2930	3170	3450	3790	4200
Nd	Neodymium	1	3.3	6.31	1297	10^{-8}	1	1575	1770	2000	2300	2740
Ni	Nickel	1	4.84	7.633	1725 ± 4	--	1.3×10^{-1}	1800	1970	2180	2430	2770
Os	Osmium	3	4.7	8.7	3318	--	2×10^{-10}	3190	3460	3800	4200	4710
P_4	Phosphorus		--	10.484	870	--	--	458	493	534	582	642
Pb	Lead	1	4.02	7.415	600.6	1.2×10^{-2}	--	988	1105	1250	1435	1700
Pd	Palladium	1	4.82	8.33	1823 ± 3	1.2×10^{-10}	3×10^{-1}	1735	1920	2150	2450	2840
Po	Polonium	3	4.7*		527	70	--	588	655	743	862	1040
Pr	Proseodymium	1	2.7	5.76	1208	9×10^{-10}	3.3×10^{-1}	1700	1890	2120	2420	2820
Pt	Platinum	2,3	5.32	9.0	2043		8×10^{-5}	2370	2590	2860	3190	3610
Pu	Plutonium				913	2×10^{-10}	1.2×10^{-1}	1780	1975	2230	2550	2980
Ra	Radium	3	3.2*	5.277	973	4×10^{-1}		830	920	1060	1225	1490
Rb	Rubidium	1	2.13	4.176	312	--	--	446	500	568	665	826
Re	Rhenium	1,2	5.1	7.87	3453 ± 20	--	10^{-10}	3340	3680	4080	4600	5220
Rh	Rhodium	3	4.75	7.46	2239	--	1.3×10^{-4}	2310	2520	2780	3110	3520
Ru	Ruthenium	3	4.60	7.364	(2700)		1.3×10^{-6}	2670	2860	3130	3480	3900
S	Sulfer		--	--	388.36	--	--	382	420	462	519	606
Sb	Antimony	1	4.08	8.639	903	6.5×10^{-1}	--	806	885	1030	1250	1560
Sc	Scandium	3	3.3	6.54	1811 ± 2	2.3×10^{-9}	5×10^{-1}	1650	1835	2070	2370	2780
Se	Selenium	1	4.72	9.75	490	--	--	516	570	636	719	826
Si	Silicon	1	4.1	8.149	1685 ± 2	--	3.3×10^{-2}	1905	2090	2330	2620	2990
Sm	Samarium	1	3.2		1345	7.3×10^{-3}		1015	1120	1260	1450	1715
Sn	Tin	2,3	4.38	7.342	505	5.3×10^{-8}	3	1520	1685	1885	2140	2500
Sr	Strontium	1	2.35	5.692	1043	9×10^{-1}	--	810	900	1005	1160	1370
Ta	Tantalum	1,3	4.12	7.88	3270	--	6×10^{-11}	3330	3630	3980	4400	4930
Tb	Terbium	3	3.09	6.74	1638	9×10^{-10}	3.3×10^{-1}	1700	1890	2120	2420	2820
Tc	Technetium	3	4.4	7.28	(2400)	--	3×10^{-7}	2760	3030	3370	3790	4300
Te_2	Tellurium	3	4.73	9.01	723	43	--	647	706	791	905	1065

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Symbol	Element	Reference	Work function φ, ev [1],[2], [6]	Ionization potential V_i,	Melting point, °K	Vapor pressure (Torr) at temperature (°K)[8]		Temperatures (°K) for vapor pressures (Torr) [8]				
						1000	2000	10^{-2}	10^{-1}	1	10	10^{2}
Th	Thorium	2	3.35		1968	--	3×10^{-6}	2680	2960	3310	3750	4340
Ti	Titanium	2	3.95	6.82	1940	--	9×10^{-3}	2010	2210	2450	2760	3130
Tl	Thallium	1	3.76	6.106	577	1.7×10^{-11}	--	882	979	1100	1255	1460
Tm	Thulium	3	3.12		1873 ± 50	5×10^{-4}	7×10^{2}	1120	1235	1370	1540	1760
U	Uranium	3	3.3	6.0	1405.5 ± 8	--	9×10^{-4}	2200	2430	2720	3080	3540
V	Vanadium	1	4.11	6.74	2190 ± 10	--	2×10^{-3}	2120	2320	2560	2850	3220
W	Tungsten	1,3	4.50	7.98	3650 ± 5	--	--	3500	3810	4180	4630	5200
Y	Yttrium	3	3.3	6.38	1773	--	1.3×10^{-5}	1905	2105	2355	2670	3085
Yb	Ytterbium	3	2.59		1097 ± 5	4×10^{-1}		830	920	1060	1225	1490
Zn	Zinc	1	3.74	9.391	692.7 ± 1	90	--	617	681	760	870	1010
Zr	Zirconium	3	3.9	6.84	2128 ± 25	--	1.6×10^{-6}	2670	2930	3250	3650	4170

*Indicates estimated value

TABLE II. - ELECTRONEGATIVITY SCALE OF THE ELEMENTS

Element symbol	Atomic number	Chemical valence (most stable)	Electro-negativity scale* [4]	Element symbol	Atomic number	Chemical valence (most stable)	Electro-negativity scale* [4]
H	1	1	2.1	Te	52	4	2.1
He	2	0	-	I	53	- 1	2.5
Li	3	1	1.0	Xe	54	0	
Be	4	2	1.5	Cs	55	1	0.7
B	5	3	2.0	Ba	56	2	0.9
C	6	± 4	2.5	La	57	3	
N	7	- 3	3.0	Ce	58	3	
O	8	- 2	3.5	Pr	59	3	
F	9	- 1	4.0	Nd	60	3	
Ne	10	0	-	Pm	61	3	
Na	11	1	0.9	Sm	62	3	
Mg	12	2	1.2	Eu	63	3	
Al	13	3	1.5	Gd	64	3	1.1 - 1.2
Si	14	4	1.8	Tb	65	3	
P	15	5	2.1	Dy	66	3	
S	16	6	2.5	Ho	67	3	
Cl	17	± 1	3.0	Er	68	3	
Ar	18	0	-	Tm	69	3	
K	19	1	0.8	Yb	70	3	
Ca	20	2	1.0	Lu	71	3	
Sc	21	3	1.3	Hf	72	4	1.3
Ti	22	4	1.5	Ta	73	5	1.5
V	23	5	1.6	W	74	6	1.7
Cr	24	3	1.6	Re	75	7	1.9
Mn	25	2	1.5	Os	76	4	2.2
Fe	26	3	1.8	Ir	77	4	2.2
Co	27	2	1.8	Pt	78	4	2.2
Ni	28	2	1.8	Au	79	3	2.4
Cu	29	2	1.9	Hg	80	2	1.9
Zn	30	2	1.6	Tl	81	1	1.8
Ga	31	3	1.6	Pb	82	2	1.8
Ge	32	4	1.8	Bi	83	3	1.9
As	33	± 3	2.0	Po	84	2	2.0
Se	34	4	2.4	At	85		2.2
Br	35	± 1	2.8	Rn	86	0	
Kr	36	0	-	Fr	87	1	0.7
Rb	37	1	0.8	Ra	88	2	0.9
Sr	38	2	1.0	Ac	89	3	1.1
Y	39	3	1.2	Th	90	4	1.3
Zr	40	4	1.4	Pa	91	5	1.5
Nb	41	5	1.6	U	92	6	1.7
Mo	42	6	1.8	Np	93	5	
Tc	43	7	1.9	Pu	94	4	
Ru	44	3,4	2.2	Am	95	3	
Rh	45	3	2.2	Cm	96	3	1.3
Pd	46	2	2.2	Bk	97	3	
Ag	47	1	1.9	Cf	98	3	
Cd	48	2	1.7	Es	99		
In	49	3	1.7	Fm	100		
Sn	50	4	1.8	Md	101		
Sb	51	3	1.9	No	102		

TABLE III. - PHYSICAL ADSORPTION

Metal Substrate	Heat of Adsorption ΔH in k cal/mole - Physical Adsorption						
	Ar	Kr	Ne	Xe	He	N_2	CO
Ag	3.5 [16]					3.6 [23]	3.2 [16]
Au							
Cr							
Cu	~ 3.1 [15]						
Fe	3.2 [16]					3.1 [16]	3.4 [16]
Mo	3.5 [46]						3.0 [46]
Ni	3.0 [17]						
Pt	3.3 [16]	4.5 [18]	1.01 [18]		3.0 [18]	3.38 [16]	3.6 [16]
Rh							
Ta				5.3 [13]			
Ti							
W	1.9 [13]	5.9 [13]		10.0 [13]			
	~ 1.9 [14]	< 4.5 [14]		8-9 [14]			
Carbon Black	4.34 [43]		1.36 [43]				
Alumina	2.80 [43]	3.46 [43]					
Porous Glass	3.79 [43]		1.56 [43]				

*The values given in the table refer to the common oxidation states of the elements listed in column 3. For some elements variation of the electronegativity with oxidation number is observed.

TABLE IV. - CHEMISORPTION FOR VARIOUS ADSORBATES

Metal Substrate	Heat of Adsorption ΔH in k cal/mole - Chemisorption										
	Ba	Cs	H_2	K	Na	N_2	O_2	Rb	Sr	CO	CO_2
Ag											
Au										9 [23]	
Cr			45 [30]								81 [23]
Cu			35 [30]							9 [23]	
Fe			32 [30]			70 [23]				46 [23]	61 [23]
Mo			40 [23]				172 [23]				89 [23]
Ni			30 [23]			10 [42]	130 [42]			42 [23]	44 [23]
			29 [41]								
Pt			30 [30]				70 [23]				
							67 [24]				
Rh			28 [30]				118 [23]				
			26 [42]				120 [24]				
Ta			45 [42]			140 [23]	212 [24]				168 [23]
			39* [30]								
Ti										153 [23]	163 [23]
W	81 [22]	68 [21]	45 [30]	59 [20]	32 [19]	95 [23]	194 [24]	60 [30]	85 [21]	82 [23]	109 [23]
		69 [30]	43.6* [29]		63 [20]	85 [50]	190 [40]				
		64 [21]	46 [41]								
		55 [26]									
Mn			17 [23]								53 [23]
Nb											132 [23]
Pd			26 [23]								

TABLE V. - ELECTRIC DIPOLE MOMENTS OF COMPOUNDS

Compound	μ (debye)	Temperature (°K)	Compound	μ (debye)	Temperature (°K)
Inorganic			$Sn I_4$	0	526
$Al Br_3$	5.14	---	TlCl	4.44	---
$Al I_3$	2.48	---	UF_4	0	313 - 356
$As Cl_3$	1.59 ± 0.01	380 - 470	Xe	0	298
$As F_3$	2.815 ± 0.025	---	Organic		
$B F_3$	0	193, 298	$C Cl_4$	0	296, 368
BrCl	0.57 ± 0.02	---	CF_4	0	193, 368
BrF	1.29	---	CO	0.10	83,298
Br_2	0	293 - 412	CO_2	0	298
ClF	0.88	273 - 356	CS_2	0	325 - 489
CsCl	10.5 ± 0.25	---	CH_4	0	193, 298
CsF	7.42 ± 0.47	---	$C_7N_7NO_3$		
CsI	10.2	873		4.83	477
H Br	0.80 ± 0.01	218 - 599			
H Cl	1.050 ± 0.004	201 - 589			
H F	1.91	305 - 374			
H I	0.42	245 - 346			
H_2O	1.85	423 - 483			
H_2O_2	2.13 ± 0.05	---			
H_2S	1.10	197 - 542			
Hg	0	674 - 743			
$HgBr_2$	0	614 - 695			
$HgCl_2$	0	599 - 701			
HgI_2	0	568 - 701			
KBr	9.1	920			
KCl	8.0	949			
KF	7.33 ± 0.24	---			
KI	9.2	898			
Kr	0	298			
NF_3	0.22	193 - 368			
NH_3	1.469 ± 0.006	274 - 457			
NO_2	0.39	297 - 397			
NaI	4.9	950			
Ne	0	82, 298			
O_3	0.52	194 - 360			
SO_2	1.633 ± 0.006	266 - 444			
$SnCl_4$	0.95	---			

TABLE VI. ELECTRICAL AND THERMODYNAMIC PROPERTIES OF COMPOUNDS

Compound	Melting point [6](°K)	Boiling point [6](°K)	Temperatures (°K) for vapor pressures (Torr), [4] 1	10	100	Heat of formation [2] (k cal)	Heat of vaporization [10] (k cal/mole)	Density [10] g/cm^3	Lattice constant [11] Å	Lattice energy [11] (eV)	Energy Gap [10] (eV)	Dipole moment μ (debye)
Ba O	2190	1650				133.1	89s	5.72	5.52	31.5	~ 4.8	7.955
Ca O	2833	--				151.71	--	2.62	4.80		6-7	
Cs Br	1009	1573	1021	1160	1345	97.468	35.99	4.43	4.29	6.35	7.0-8.0	--
Cs Cl	919	1573	1017	1157	1342	106.48	35.69	3.97	4.11	6.6	≥ 8.0	10.5 ± 0.25
Cs F	956	1524	985	1117	1298	131.97	34.3	3.58	6.01	7.53	10.0	7.42 ± 0.47
Cs I	894	1553	1111	1146	1328	83.752	--	4.51	4.56	6.04	≥ 6.3	10.2
H Cl	158.9	188.4	122.4	136.6	159.2	22.03	3.860	1.194	--		--	1.05
H F	189.5	292.9	--	207.4	245.0	63.991	1.8	0.987	--		--	1.91
K Br	1003	1656	1068	1255	1410	94.027	48.9s	2.75	6.59	6.91	7.8	9.1
K Cl	1063	1680	1094	1241	1437	104.30	49.3s	1.98	6.28	7.15	8.5	8.0
K F	1153	1775	1158	1312	1518	134.10	--	2.48	5.34	8.22	10.9	7.33 ± 0.24
K I	996	1597	1018	1160	1353	78.758	34.7	3.12	7.05	6.58	≥ 6.2	9.2
Li Br	823	1583	1021	1161	1349	83.728	35.4	3.46	5.49	8.21	≈ 8.5	
Li Cl	887	1655	1056	1205	1402	97.420	--	2.06	5.13	8.64	~ 10	
Li F	1143	1954	1320	1484	1698	145.54	--	2.29	4.02	10.4	--	
Li I	719	1444	996	1114	1266	64.994	30.2	4.06	6.00	7.55	≥ 5.9	
Na Br	1023	1665	1079	1225	1421	86.333	38.7	3.20	5.96	7.57	7.7	
Na Cl	1073	1738	1138	1290	1493	98.36	40.4	2.16	5.63	7.95	8.6	
Na F	1265	1977	1350	1513	1728	136.30	8.03	2.79	4.62	9.24	≥ 10.5	
Na I	924	1577	1040	1176	1356	69.46	38.2	3.66	6.46	7.1	≥ 5.8	4.9
Rb Br	965	1625	1054	1196	1387	96.06	37.12	3.35	6.85	6.65	7.7	
Rb Cl	995	1654	1065	1210	1406	104.97	36.9	2.76	6.54	6.91	8.2	
Rb F	1070	1681	1194	1289	1441	133.31	46.4	2.88	5.64	7.87	10.4	
Rb I	920	1578	1021	1157	1345	80.77	35.9	3.55	7.33	6.46	≥ 6.1	
Sr O	2703	--	2341	2535	--	140.7	--	4.7	5.14	33.2	≈ 6	
Th I_4						291.76					--	
Th O_2	3323	4673				330.95	145	10.03			--	

S - Heat of Sublimation

TABLE VII. - ELEMENTAL PROPERTIES OF SELECTED METALS

Property	Tungsten	Tantalum	Molybdenum	Rhenium	Niobium (Columbium)	Iridium	Osmium	Pt
Atomic number	74	73	42	75	41	77	76	78
Atomic weight, AMU	183.85	180.95	95.94	186.31	92.91	192.2	190.2	195.09
Atomic volume	9.53	10.9	9.41	9.3	10.83	8.58		
Lattice type	BCC	BCC	BCC	Hex close pack	BCC	FCC	Hex close pack	
Lattice constant, $(293^{\circ}K)\mathring{A}$	3.1585	3.3026	3.1468	a = 2.760, C = 4.458	3.3004	3.8389		
Density $(293^{\circ}K)$ Kg/m^3	19300	16600	10200	21030	8570	22540		
Thermionic work function ev. $A[amp(cm)^{-2}(^{\circ}K)^{-2}]$	4.50	4.12	4.20	5.1	3.99	4.57		
Ionization potential ev.	7.98	7.88	7.10	7.87	6.88	9.0		
Vapor pressure $(2000^{\circ}K)$ Torr	---	6×10^{-11}	2×10^{-7}	10^{-10}	5×10^{-9}	5×10^{-8}		
Electronegativity	1.7	1.5	1.8	1.9	1.6	2.2		
Melting point, $^{\circ}K$	3683	3269	2883	3453	2770	2727		
Specific heat, joule/$Kg^{\circ}K(293^{\circ}K)$	134	150	255	139	272	134		
Elect. resistivity microns$(293^{\circ}K)$	0.055	0.135	0.057	0.211	0.141	0.053		
Surface atom density	1.003×10^{15}	0.917×10^{15}	1.01×10^{15}		0.918×10^{15}	0.679×10^{15}		
Heat of fusion, Kcal/mole [10]	8	1	6.6	5	6	6		
Heat of vaporization, Kcal/mole [10]	191	180	157.5	118	174.8	143		
Spectral emissivity ($\lambda \sim 0.65\mu$)	0.45 $(1173^{\circ}K)$	0.46 $(1173^{\circ}K)$	0.37 $(1273^{\circ}K)$	0.42	0.49	0.30	0.44	0.30

TABLE VIII. - SELECTED DATA ON ADSORBATE ELEMENTS

Element	Atomic number	Melting point[5] (^{o}K)	Boiling point[2] (^{o}K)	Heat of vaporization[10] Kcal/mole	Univalent ion radii [4] A^{o}	Electronic polarizability [9] $cm^3 \times 10^{-24}$
Ar	18	83.6	87.5	1.558	1.54	1.62
Ba	56	983.0	1895.0	35.7	1.53	1.55
Cl_2	17	170.0	238.6	4.878	1.81	3.66
Cs	55	301.8	978.0	15.78	1.69	2.42
F_2	9	50.0	87.0	1.562	1.36	1.04
H_2	1	14.0	20.4	0.215	2.08	0.1
He	2	1.6	4.3	0.02	0.93	0.201
I	53	387.0	457.5	14.88 s	2.16	7.10
K	19	336.4	1030.0	18.3	1.33	0.83
Kr	36	116.6	120.3	2.156	1.69	2.46
Li	3	453.69	1599.0	30.8	0.60	0.029
Na	11	370.98	1156.0	24.6	0.98 [27]	0.179
Ne	10	24.51	27.3	0.431	1.12	0.390
N_2	7	63.3	77.4	1.335	2.47	---
O_2	8	54.2	90.2	1.630	1.76	3.88
Rb	37	312.0	974.0	16.54	1.48	1.4
Xe	54	161.0	166.1	3.021	1.90	3.99

s = Heat of sublimation.

TABLE IX. - ELEMENTAL PROPERTIES OF SELECTED ADSORBATES

Property	Cesium	Barium	Fluorine	Oxygen	Chlorine	Iodine	Thorium
Atomic number	55	56	9	8	17	53	90
Atomic weight	132.91	137.34	18.998	15.999	35.453	126.90	232.038
Crystal form	bcc	bcc	---	---	---	---	fcc
Lattice constant, Å	a = 6.2 d = 5.4	a = 5.02 d = 4.2	---	d = 1.2	---	---	5.0
Atomic radius, Å	2.62	2.24	0.68		0.97	1.35	1.8
Ionic radius, Å	1.69	1.35	1.36	1.4	1.81	2.16	0.99
Density (Kg/m^3) - solid (293°K)	1900	3500	1140 l	1140 l	1507 l	4940 l	12000
Melting point (°K)	301.8	983	50	54.2	172.2	387	1968
Boiling point (°K)	978	1895	87	90.2	239.1	---	4500
Latent heat of fusion, Kcal/mole [10]	0.51	1.83	0.122	0.106	1.531	3.74	3.7
Latent heat of vaporization, Kcal/mole [10]	15.78	35.7	1.562	1.630	4.878	14.88 s	120
Specific heat (joules/Kg °K) [2]	217	284	---	973	481	142	---
Ionization potential (volts) [2]	3.87	5.19	17.34	13.550	12.952	10.6	---
Electronic work function (ev.)	1.81	2.49	---	---	---	---	3.35
Electronegativity	0.7	0.9	4.0	3.5	3.0	2.5	1.3
Electronic polarizability of ions [9] $Cm^3 \times 10^{-24}$	2.42	1.55	1.04	3.88	3.66	7.10	---

l = liquid state.
s = sublimation.

TABLE X. - EMISSION PROPERTIES OF VARIOUS FACES OF TUNGSTEN SINGLE CRYSTAL

AS TABULATED IN REFERENCE [3]*

Method used	Index of Crystal Face (φ in eV.)														
	001	011	012	013	021	100	110	111	112	116	122	123	211	233	310
	4.52	5.2				4.56	4.68	4.39	4.69	4.39					
	4.56					4.59	4.68	4.39	5.3	4.39					
	4.59					4.56	4.58	4.38	4.69	4.39					
	4.52					4.56	4.66	4.4	4.69	4.29					
TE	4.52					4.52	4.58	4.38	4.65	4.30					
							4.58	4.43[49]							
							5.3								
							5.3								
PE		5.85	4.34	4.31				4.39	4.76	4.30	4.35	4.52	4.50	4.46	4.30
									4.50						
		5.7	<4.39		5.0	4.6	5.8	3.9	4.93	4.3	4.35	4.52		4.46	4.31
			4.34			4.97	5.6	4.64	4.8	4.49					
FE						4.6	4.68	4.4	4.9	4.2					
						4.6	>4.9	4.2		4.3					
						4.72[48]	5.5	4.39							
							6.0	4.3							
							4.6								

TE = Thermionic emission
PE = Photoelectric emission
FE = Field emission

*See Table XIX also

TABLE XI. - CHEMICAL ELEMENTS ON SUBSTRATES - REFERENCE [3]

Metal - Film	Work function φ in eV by thermionic emission except as noted	Remarks
Ti-Cl	4.40	
Ti-Cs	1.07	Optimum coating at Cs pressure of 10^{-6} to 10^{-2} Torr.
Ni-H	4.98 CPD	
Ni-O	6.34 CPD	
Ni-O	6.36 PE	
Ni-Cs	1.65	Optimum coating (10^{-6} to 10^{-2} Torr).
Ni-Ba	2.60	
Nb-Cs	1.02	Optimum coating (10^{-6} to 10^{-2} Torr).
Mo-Cs	1.22	Optimum coating (10^{-6} to 10^{-2} Torr).
Mo-Cs	1.68	
Mo-Th	2.58 TE, PE	
Ag-O-Cs	0.8 PE	
Ag-O-Cs	1.0	
Hf-O	5.1	
Hf-Cs	3.62	Optimum coating (10^{-6} to 10^{-2} Torr).
Ta-H	4.53 CPD	
Ta-N	4.50 CPD	
Ta-Cs	1.11	Optimum coating (10^{-6} to 10^{-2} Torr).
Ta-Th	2.52	
W-H	5.80 CPD	
W-Li	1.83	
W-Be	4.50	
W-N	6.88 CPD	
W-O	5.34 PE	

TABLE XI. - CHEMICAL ELEMENTS ON SUBSTRATES - REFERENCE [3] (con't.)

Metal - Film	Work function φ in eV by thermionic emission except as noted	Remarks
W-O	6.24 PE	
W-O	6.28 CPD	
W-Na	1.76	
W-Na	2.10 PE	
W-K	1.64	
W-Ca	2.40	
W-Sr	2.20	
W-Zr	3.14 TE, PE	
W-Zr	3.15	
W-Cs	1.1	Optimum coating.
W-Cs	1.36	
W-Cs	1.36 TE, PE	
W-Cs	1.38	
W-Cs	1.41	Optimum coating at Cs pressure of 10^{-6} to 10^{-2} Torr.
W-Cs	1.44 CPD	
W-Cs	1.50 PE	
W-Cs	1.64 CPD	
W-Cs	1.70 PE	
W-Ba	1.10 PE	
W-Ba	1.56	
W-Ba	1.56	
W-Ba	1.66	
W-Ba	1.90	
W-Ba	2.01	

TABLE XI. - CHEMICAL ELEMENTS ON SUBSTRATES - REFERENCE [3] (con't)

Metal - Film	Work function φ in eV by thermionic emission except as noted	Remarks
W-Th	2.62 PE, TE	
W-Th	2.66	
W-Th	2.67	
W-Th	2.69	
W-Th	2.73	
W-Th	2.77	
W-Th	2.86 TE, PE	
W-H-K	1.80	
W-O-Na	1.72	
W-O-K	1.76	
W-O-Cs	0.72	
W-O-Cs	1.44	
W-O-Ba	1.34	
W-O-Ba	1.34	
Re-Cs	1.98	Optimum coating (10^{-6} to 10^{-2} Torr).
Re-Ba	2.3	
Re-Th	2.58	In 1373^{o}-1573^{o} K temperature range.
Re-Th	3.15	
Re-Th	3.16	Monolayer coating.
ThO_2-Cs	1.0	Optimum coating.

TE = Thermionic emission.
PE = Photoelectric emission.
CPD = Contact potential difference.

TABLE XII. - CHEMICAL COMPOUNDS ON SUBSTRATES - REFERENCE [3]

Substrate - material	Work function φ in eV by thermionic emission except as noted	Remarks
Al-BaO	1.80	Activated.
Ti-BaO	1.58	Heat-activated at 1073° to 1173° K.
Cr-BaO	1.54	"
Cr-BaO	1.72	"
Fe-BaO	1.61	"
Fe-BaO	1.83	"
Ni-SrO	2.0	Temperature 675° to 850° K.
Ni-BaO	1.27	
Ni-BaO	1.32	Activated.
Ni-BaO	1.35	Activated.
Zr-BaO	1.48	Activated.
Zr-BaO	1.5	Temperature 670° to 870° K.
Zr-BaO	1.53	Activated.
Mo-CaO	2.1	Temperature 820° to 920° K.
Mo-SrO	1.15	Temperature 1000° K.
Mo-SrO	1.2 - 1.1	Temperature 550° to 900° K.
Mo-BaO	1.1	Temperature 1000° K.
Mo-BaO	1.2 - 1.0	Temperature 550° to 900° K.
Mo-BaO	1.22	Temperature 1000° K.
Mo-BaO	1.39	Activated.
Mo-BaO	1.40	Activated.
Mo-CsF-Cs	1.38 ±0.05	
Ta-SrO	1.3	Temperature 600° to 870° K.

TABLE XII. - CHEMICAL COMPOUNDS ON SUBSTRATES - REFERENCE [3] (Con't.)

Substrate - material	Work function φ in eV by thermionic emission except as noted	Remarks
Ta-BaO	1.15	Temperature 1000° to 870° K.
Ta-BaO	1.3 - 1.0	Temperature 600° to 900° K.
Ta-BaO	1.48	Activated.
Ta-BaO	1.58	Activated.
W-CaO	2.1	Temperature 820° to 920° K.
W-SrO	1.2 - 1.1	Temperature 550° to 900° K.
W-BaO	1.1	Temperature 1000° K.
W-BaO	1.2 - 1.0	Temperature 550° to 900° K.
W-BaO	1.34	Activated.
W-BaO	1.36	Activated.
$W-WO_3$	9.22	
$W-ThO_2$	1.5	Activated at 2150° K.
$W-ThO_2$	1.6	
$W-ThO_2$	2.4	Ba impurity present.
$W-ThO_2$	2.5	Temperature 1980° K.
$Ir-ThO_2$	6.2	
Pt-MgO	3.19	
Pt-CaO	2.52	
Pt-CaO	3.33	
Pt-SrO	1.86	
Pt-SrO	1.9	Temperature 600° to 900° K.
Pt-SrO	1.37	Activated.
Pt-SrO	1.68	
Pt-SrO	1.71	Activated.

TABLE XII. - CHEMICAL COMPOUNDS ON SUBSTRATES - REFERENCE [3] (Con't.)

Substrate - material	Work function φ in eV by thermionic emission except as noted		Remarks
$Pt-ThO_2$	2.89		
$Pt-ThO_2$	3.18		
Pt-BaO/SrO	1.51 - 1.89		
Au-BaO	1.81		Activated.
Au-BaO	1.90		Activated.
Ag_2O-Cs	0.75		
Ag_2O-Cs	0.75	PE	
W_2O-Cs	0.71		
W_2O-Cs	0.71	PE	
W_2O-Ba	1.1		
W_2O-BaO	1.0 - 1.1	PE	Activated.
W_2O-Ba/BaO	2.43		Heat activated at 1073° to 1173° K.

PE = Photoelectric emission.

TABLE XIII. - MINIMUM EFFECTIVE WORK FUNCTIONS FOR Cs SYSTEMS

Surface	Coating	Measured minimum effective work function (eV)		Remarks
Mo	Cs-CsH	~1.3	[33]	
Mo	Cs-CsF	1.38 ±0.05	[32]	
Mo	Cs-H	1.32	[45]	
Mo	Cs-H	~1.4	[33]	
Mo	Cs-H	1.12	[44]	
Mo	Clean	4.20	[34]	
	Cs($\sigma = \sigma_m$)	1.50 ±0.05		
	Cs($\sigma = \sigma_\infty$)	1.82 ±0.03		
W	Clean	4.52	[34]	
	Cs($\sigma = \sigma_m$)	1.53 ±0.05		$\sigma = 19\times10^{14}$
	Cs($\sigma = \sigma_\infty$)	1.83 ±0.03		
W	O	5.16	[34]	
W	Cs-O($\sigma = \sigma_m$)	1.13	[34]	$\sigma \sim 1.2\times10^{14}$
W	Cs-O	1.3	[44]	
W	Cs-F	1.3	[44]	
Re	Clean	4.85	[34]	
	Cs($\sigma = \sigma_m$)	1.45 ±0.05		
	Cs($\sigma = \sigma_\infty$)	1.80 ±0.03		
Ta	O	4.56		
Ta(110)	Clean	4.91	[35]	
	Cs($\sigma = \sigma_m$)	1.52		
	Cs($\sigma = \sigma_\infty$)	1.91		
Ta(110)	Clean	4.84	[35]	
	Cs($\sigma = \sigma_m$)	1.47		
	Cs($\sigma = \sigma_\infty$)	1.91		
Ta(near 316)	Clean	4.44	[35]	
	Cs($\sigma = \sigma_m$)	1.61		
	Cs($\sigma = \sigma_\infty$)	1.91		
Ta	Cs-F	1.0	[44]	
Ni	Cs($\sigma = \sigma_m$)	1.44 ±0.05	[37]	$T_e/T_{cs} \simeq 1.75$
Ni	CsH	1.42 ±0.05		
W	CsF	1.18 ±0.02	[47]	$\theta \geq 1$, $T \sim 600^\circ$ K, 211 F.E.

TABLE XIV. - Cs ON SUBSTRATES

Metal	Calculated minimum φ_e [38] Cs at T = 473° K		Experimental minimum φ_e with optimum Cs coverage			Typical values of β for cesium on different substrates [39]
	(ev)	emitter temp. (1000/T)	$\varphi_{e\,min}$ (ev)		σ_m(atoms/cm^2)	
Ti	1.78	633	1.07	[3]		1.92
V	1.79	666				1.95
Cr	1.79	588				1.86
Mn	1.80	495				2.24
Fe	1.79	602				1.95
Co	1.79	610				1.95
Ni	1.79	562	1.65	[3]		1.85
			1.4	[44]		
Zr	1.76	775	3.93	[3]		1.77
Nb	1.78	847	1.02			1.66
Mo	1.78	813	1.50±0.05	[34]		1.62
Tc	1.78	806				1.63
Ru	1.78	787				1.67
Rh	1.78	757				1.70
Pd	1.77	595				1.71
Hf	1.78	820	3.62	[3]		1.65
Ta	1.78	870	1.11	[3]		1.62
W	1.77	840	1.53±0.05	[34]	1.9×10^{14}	1.60
Re	1.77	820	1.45±0.05	[34]		1.61
Os	1.78	685				1.70
Ir	1.77	741				1.68
Pt	1.77	769				1.66

TABLE XV. - WORK FUNCTIONS OF OXIDES.

(Reference [3] except as noted)

Oxide	Work function φ (eV)
BaO	0.99
	1.00
	1.0
	1.1
	1.1
	1.1
	1.3
	1.4
	1.44
	1.4 - 1.6
	1.57
	1.63
CaO	1.6 ±0.2
	1.77
	1.9
	2.37
Cs_2O	0.99 - 1.17
FeO	3.85
HfO_2	2.82 (activated)
	3.60
	3.76 (activated)
	5.84
NiO	5.55
SrO	1.27
	1.4
	1.4 - 1.6
SrO	2.03
	2.07
	2.12
	2.58
ThO_2	1.66 (activated)
	2.54
	2.55
	2.55
	2.57
	2.60
	2.6
	2.67
	2.7
	2.71
	2.74
	2.8
	2.8
	3.06
	3.07
Ta_2O_5	4.65
TiO_2	3.87 (activated)
	6.21 (unactivated)
WO_2	4.96
CsF	~3.2 reference [32]

TABLE XVI. - WORK FUNCTIONS OF CARBIDES AND NITRIDES.

Reference [3]

Compound	Work function φ (eV) at temperature in °K	Compound	Work function φ (eV) at temperature in °K
HfC	2.04	TiC	2.35
	3.25 (1550°K)		2.72
	3.66 (2370°K)		3.35
	3.85 (2200°K)		3.6 (1800°K)
	4.0 (1300-2100°K)		4.12 (1800°K)
	4.15 (1800°K)		3.53 (300°K)
	3.47 (300°K)		3.74 (1400°K)
	3.65 (1400°K)		3.82 (2000°K)
	3.76 (2000°K)		
		W_2C	2.6
MoC	3.80 (1800°K)		4.42
			4.58 ±0.08
Mo_2C	3.85 (1465°K)		
		WC	3.60 (1465°K)
MbC	2.24		
	3.85 (1500°K)	UC	2.70
	3.83 (2370°K)		2.94
	4.02 (300°K)		3.21 (1800°K)
	3.74 (1400°K)		3.3 (1350-1500°K)[31]
	3.58 (2000°K)		3.97 ±0.015
			4.57
TaC	3.05	NbN	3.92 (1950°K)
	3.14		
	3.17 ±0.06	TaN	4.00 (1600°K)
	3.64 (2200°K)		
	3.77 (2370°K)	ThN	3.1
	4.15 (1800°K)		
	3.93 (300°K)	TiN	2.92
	3.77 (1400°K)		3.75 (2000°K)
	3.65 (2000°K)		

TABLE XVII. - NUMBER OF ADSORBTION SITES

Adsorbate	Number of atoms in monolayer covering of (100) plane W	Ta	Mo
Sites available	1.003×10^{15}	0.917×10^{15}	1.01×10^{15}
Cs	5×10^{14}	4.585×10^{14}	5.005×10^{14}
Ba	1.003×10^{15}	0.917×10^{15}	1.01×10^{15}
Th	1.003×10^{15}	0.917×10^{15}	1.01×10^{15}
F	1.003×10^{15}	0.917×10^{15}	1.01×10^{15}
O	1.003×10^{15}	0.917×10^{15}	1.01×10^{15}
Cl	5×10^{14}	4.585×10^{14}	5.005×10^{14}
I	5×10^{14}	4.585×10^{14}	5.005×10^{14}
Cs-F F	1.003×10^{15}	0.917×10^{15}	1.01×10^{15}
Cs-F Cs	5×10^{14}	4.585×10^{14}	5.005×10^{14}
Ba-O O	1.003×10^{15}	0.917×10^{15}	1.01×10^{15}
Ba-O Ba	1.003×10^{15}	0.917×10^{15}	1.01×10^{15}
Cs-Cl Cl	5×10^{14}	4.585×10^{14}	5.005×10^{14}
Cs-Cl Cs	5×10^{14}	4.585×10^{14}	5.005×10^{14}

TABLE XVIII. - SELECTED VAPOR PRESSURES

Gas	Temperature (^{o}K) for vapor pressures (Torr)									Melting point (^{o}K)
	10^{-10}	10^{-8}	10^{-6}	10^{-4}	10^{-2}	1	10	100	760	
F_2						50.5	59	70.5	85.2	53.5
Cl_2				103	123	153	172	201	239	172.2
I_2	161	178	199	226	262	312	345	388	456	387.0
O_2									90.2	54.0

TABLE XIX. - WORK FUNCTIONS IN CERTAIN CRYSTALLOGRAPHIC DIRECTIONS ON MOLYBDENUM AND TUNGSTEN

(A) Molybdenum

Crystal direction	Thermionic Emission	
	Coomes & Boeck [56] Projection diode technique	Coomes(Gardner) [ ] Projection diode technique
110	5.4 ±0.2 (A = 2500 ±1500)	4.83 4.81
112	4.5 ±0.1 (A = 85 ±35)	4.69 4.72
001	4.5 ±0.1 (A = 118 ±30)	4.57
111	4.3 ±0.1 (A = 25 ±10)	4.40 4.42
116	4.2 ±0.1 (A = 17 ±8)	4.31 4.33
	Work function values corrected for elastically scattered electrons. Crystals grown via the Robinson-plus-torsion technique.	Low index directions in error due to elastically scattered electrons. Crystals grown via the Robinson-plus-torsion technique. Values are for 2 different crystals.

TABLE XIX. - Cont. WORK FUNCTIONS IN CERTAIN CRYSTAL DIRECTIONS ON MOLYBDENUM AND TUNGSTEN

(B) Tungsten

Thermionic Emission

Crystal direction (hhk)	Nichols [52] 5 mil tungsten wire in electron projection tube	Smith [53] Basic apparatus same as Nichols	Gienapp [51] 0.13 mm wire in modified projection tube	Hughes et al [54] 3 mil wire in electron projection tube	Farnsworth et al [55] Parallel crystal surface	Coggins & Stickney [49] Basic apparatus same as Nichols	Coomes & Boeck [56] Projection diode technique
110	4.68*(A = 15)	5.29 est	5.2	5.25 ±0.05			5.0 ±0.2 (A = 320 ±200)
112	4.69 (A = 125)	4.64 (A = 110) 4.65 (A = 118)	5.3	5.25 ±0.05		4.71	4.7 ±0.1 (A = 50 ±30)
001	4.56 (A = 117)	4.52 (A = 105)	4.6		4.59 ±0.02		4.6 ±0.1 (A = 130 ±40)
111	4.39 (A = 35)	4.37 (A = 47) 4.38 (A = 54) 4.39 (A = 54)	4.2			4.43(A ≈ 32)	4.4 ±0.1 (A = 50 ±30)
116	4.39† (A = 53)	4.29 (A = 40) 4.29 (A = 40)					4.3 ±0.1 (A = 35 ±15)
	Reflected electrons were not eliminated. Filament heated with direct current (d-c etch). Tungsten crystal grown by Robinson technique.	Filament heated w/AC. Multiplicity of values due to different azimuthal directions on same tungsten filament. Crystal grown by Robinson technique.	Filament heated w/AC. Reflected electrons from anode eliminated. Vacuum - 2×10^{-8} Torr.	Φ(112) measured in two directions. Electron micrograph showed microstructure of (110) facets on (112) planes. Vacuum - 5×10^{-10} Torr.	Low power electron microscope. Outgassed for 2400 hours. Vacuum - ~10^{-8} Torr.	Filament G.E. 218 wire w/diameter 2.96 mils. Single crystals grown by Robinson technique. Gradual emission decay observed (contaminant?). Vacuum - ~10^{-9} Torr.	Phosphor brightness measured by photometer. Data corrected for electron scattering.

*Believed to be in error (see Smith [53]).

†Miller index questionable [(115), (116), (117)].

TABLE XX. - DESORPTION ENERGIES

Adsorbate	Latent heat of evaporation (eV)[2]	Polycrystalline substrate	Desorption energy (eV)	Reference
Ag	2.6	Mo	1.9	57
		Mo	1.5	58
Au	3.6	Mo	4.2	59
		W	3.6 ±0.5	60
Cs	0.7	W	3.6	61
		W	2.9	21
Cu	3.2	W	3.5 ±0.5	60
H	0.009	W	2.8	62
		W	1.3	63
K	0.8	W	2.9	61
Li	1.4	W	3.8	64
Rb	0.8	W	2.6	65

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